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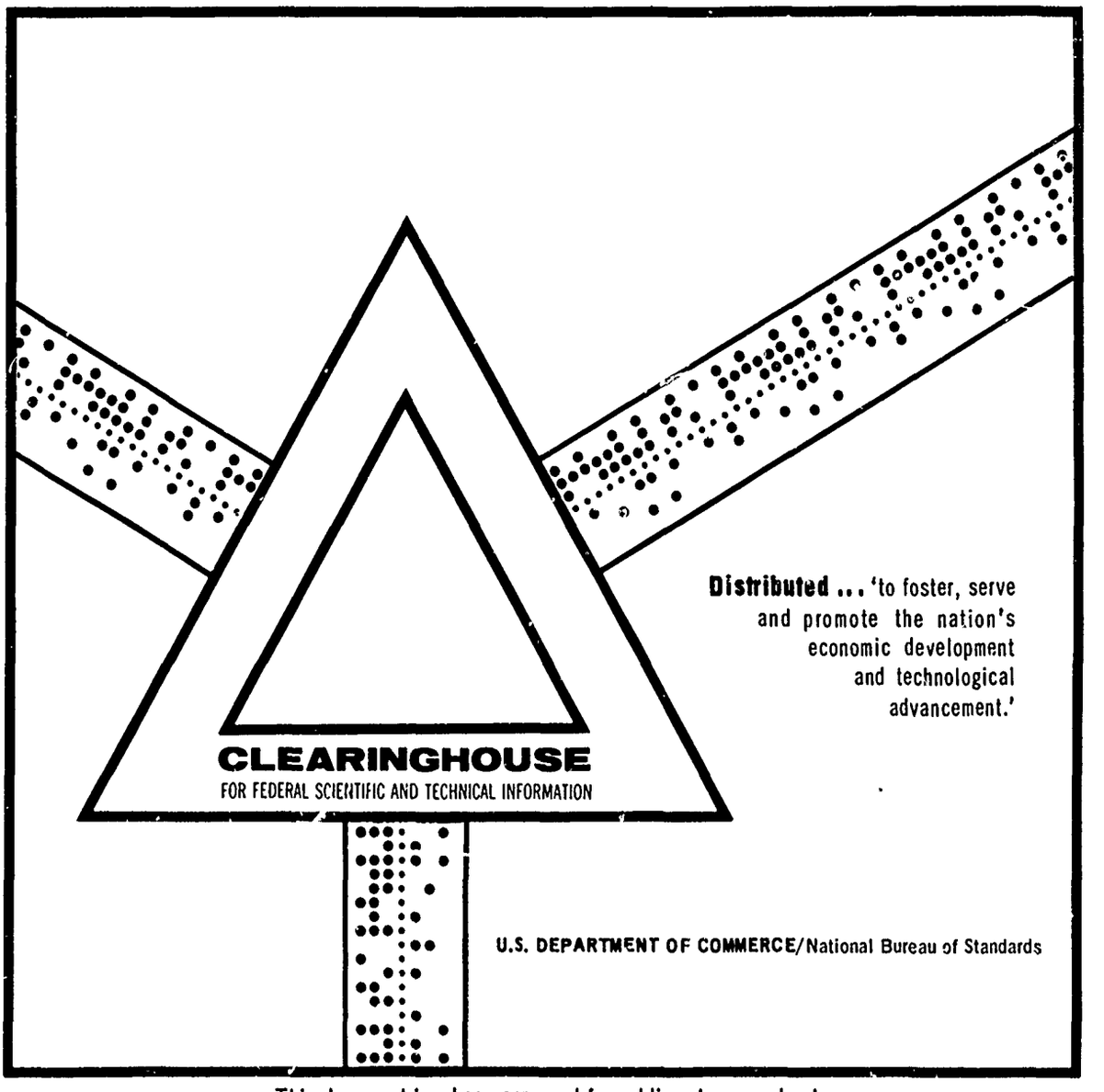
PROBABILITY ANALYSIS OF OCULAR DAMAGE DUE TO LASER RADIATION THROUGH THE ATMOSPHERE

Paul H. Deitz

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland

September 1969



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MEMORANDUM REPORT NO. 2012

PROBABILITY ANALYSIS OF OCULAR DAMAGE DUE TO LASER RADIATION THROUGH THE ATMOSPHERE

by

Paul H. Deltz

September 1969

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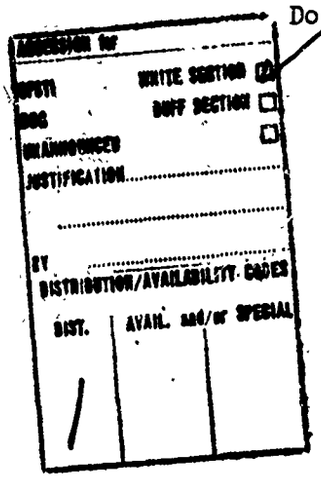

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B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

MEMORANDUM REPORT NO. 2012

SEPTEMBER 1969

PROBABILITY ANALYSIS OF OCULAR DAMAGE DUE TO LASER RADIATION THROUGH THE ATMOSPHERE

Paul H. Deitz

Signature and Propagation Laboratory

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RDT&E Project No. 1T061102A31C

A B E R D E E N P R O V I N G G R O U N D, M A R Y L A N D

B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

MEMORANDUM REPORT NO. 2012

PHDeitz/emj
Aberdeen Proving Ground, Md.
September 1969

PROBABILITY ANALYSIS OF OCULAR DAMAGE DUE TO LASER RADIATION THROUGH THE ATMOSPHERE

ABSTRACT

A mathematical model is developed which predicts the probability of ocular damage occurring to personnel illuminated by a pulsed laser beam as a function of the appropriate optical and atmospheric parameters. The evaluation includes terms for the laser output energy and divergence, and atmospheric parameters of attenuation and scintillation. Sample computations are shown, and a safety nomograph is developed to facilitate the eye hazard analysis.

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TABLE OF CONTENTS

		Page
	ABSTRACT	3
	LIST OF ILLUSTRATIONS	7
I.	INTRODUCTION	9
II.	PROPAGATION IN A HOMOGENEOUS MEDIUM	9
III.	SCINTILLATION EFFECTS	11
IV.	EYE DAMAGE MODEL	14
V.	SAMPLE COMPUTATIONS	15
VI.	RAYLEIGH CALCULATIONS	19
VII.	SAFETY NOMOGRAPH	21
VIII.	DISCUSSION	23
	ACKNOWLEDGMENT	24
	REFERENCES	25
	APPENDIX - TWELVE EYE SAFETY NOMOGRAPHS	27
	DISTRIBUTION LIST	41

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LIST OF ILLUSTRATIONS

Figure		Page
1.	Cross Section of Pulsed Laser Beam at 1000 m	12
2.	Probability of Damage versus Range for Strong Turbulence (Ω = 0.44 μsr, E_o = 0.1 J), Log-Normal Distribution	16
3.	Probability of Damage versus Range for Intermediate Turbulence (Ω = 0.44 μsr, E_o = 0.1 J), Log-Normal Distribution	17
4.	Probability of Damage versus Range for Weak Turbulence (Ω = 0.44 μsr, E_o = 0.1 J), Log-Normal Distribution . .	18
5.	Probability of Damage versus Range (Ω = 0.44 μsr, E_o = 0.1 J), Rayleigh Distribution	20
6.	Eye Safety Nomograph ($C_n = 5 \times 10^{-7}\ m^{-1/3}$, σ_A = 0.05/km) . .	22

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I. INTRODUCTION

With the advent of the laser, new interest has arisen in the study of light transmission through the atmosphere. Efforts are widespread to utilize coherent light sources in systems built for long-distance communications, guidance, and optical ranging. However, the characteristics of high power and narrow bandwidth which make lasers applicable to such systems also create an eye hazard problem for personnel who may be illuminated by a beam.

During the past year, studies were initiated to determine the potential eye hazard to personnel illuminated by optical radar. This paper describes a model which attempts to evaluate the likelihood of ocular damage occurring as a function of the influential optical and atmospheric parameters. The analysis yields a computation for the percentage area of a transmitted beam cross section which lies above a chosen level of threshold energy density, with range as the independent variable. The threshold energy density is defined for incidence at the cornea. The formulation includes a factor which lowers the beam energy density at a given range with increasing divergence, an atmospheric attenuation coefficient to account for the effects of Rayleigh and Mie scattering and water vapor absorption, and a perturbation factor for the effects of scintillation.

II. PROPAGATION IN A HOMOGENEOUS MEDIUM

The beam divergence of a laser can be defined in units of steradians as

$$\Omega = \frac{A}{L^2} , \qquad (1)$$

where A is the cross sectional area at range L through which passes a given fraction of the total laser output energy E_o in joules. Arbitrarily choosing a value of seven-tenths for the fraction of energy, the mean energy density of a beam cross section in vacuo can be given as

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$$\bar{E} = \frac{0.7\ E_o}{A} = \frac{0.7\ E_o}{\Omega L^2} . \qquad (2)$$

Since in transmission through a homogeneous atmosphere the average energy density is further lowered by scattering and absorption effects, an exponential term owing to Bouguer[1*] can be introduced as

$$\exp(-\sigma_A L). \qquad (3)$$

Here σ_A is the atmospheric attenuation coefficient and is given to account for the effects of Rayleigh and Mie scattering as well as for water vapor absorption. Table I lists values for σ_A (in units of inverse km) for various degrees of attenuation. If the "visibility" V is known, then the atmospheric attenuation coefficient can be computed by

$$\sigma_A = \frac{3.9}{V} . \qquad (4)$$

Consideration of beam divergence, molecular and particulate scattering, and water vapor absorption thus gives the average energy density at range L as

$$\bar{E} = \frac{0.7\ E_o \exp(-\sigma_A L)}{\Omega L^2} . \qquad (5)$$

Table I. Values for σ_A

Condition	σ in km^{-1}
Very clear	0.05-0.07
Clear	0.07-0.20
Light haze	0.20-0.40
Haze	0.40-0.60
Dense haze	0.60-1.00
Fog	> 1.00

*References are listed on page 25.

III. SCINTILLATION EFFECTS

The perturbation of $\overline{E}$ due to scintillation effects is now considered. The atmospheric medium is typically inhomogeneous in temperature; hence the atmosphere is inhomogeneous in the index field associated with optical density. Thus when an optical beam is transmitted through the atmosphere, rays in the beam are refracted and diffracted randomly as they travel through the medium. After transmission through the atmosphere a few hundred meters or more, the cross section of an optical beam becomes inhomogeneous in intensity as rays are diverted from some portions of the beam to others. Figure 1 shows the cross section of a laser beam photographed after transmission over a path of 1 km at a height of 2 m above the ground. The picture was taken with an optical system which is essentially a telescope with a 61-cm entrance aperture.[2] The receiver is arranged to give an image of the distribution of energy over the 61-cm entrance aperture much as though the beam were simply directed to a matte surface and photographed from the side. In the absence of scintillation effects, the cross section would have been homogeneous in energy density, the magnitude given by Equation (5).

The distribution of energy illustrated by Figure 1 can be described by a frequency distribution curve, giving the probability of various levels of energy occurring as a function of energy. Tatarski[3] has predicted that the intensities in a beam cross section are log-normally distributed. In addition, for infinite plane wave propagation in the atmosphere, he has given the variance of the distribution curve as

$$\sigma_T^2 = 1.23\, C_n^2 k^{7/6} L^{11/6}, \qquad (6)$$

where C_n is the index structure coefficient, k is the wavenumber of the light, and L is the path length. The coefficient C_n can be understood as a strength parameter for the turbulence. It is proportional to the magnitude of the temperature fluctuations in the medium and is also related to the average vertical temperature gradient over the ground. Typical values of C_n given by Davis[4] are shown in Table II. Thus all

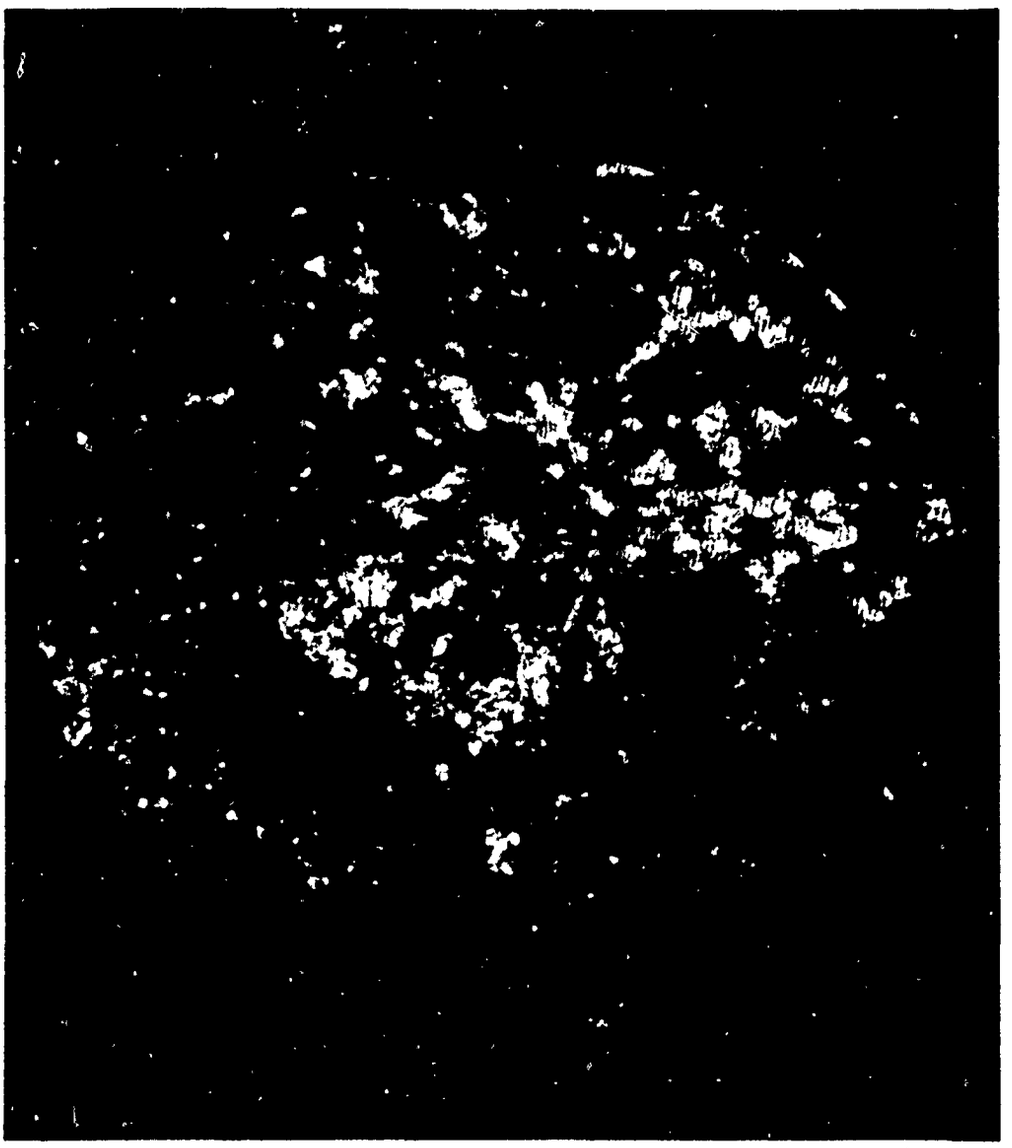

Figure 1. Cross Section of Pulsed Laser Beam at 1000 m

degrees of inhomogeneity in the atmospheric index field are related to a C_n of a particular magnitude. The evaluation given in Equation (6) predicts that the standard deviation σ_T of the distribution curve characterizing a beam cross section increases essentially as the product of L and C_n. Thus for long ranges in the atmosphere, there would be a small but finite probability of encountering very intense concentrations of energy in the beam cross section.

Table II. Typical Values of C_n

Weak turbulence*	$C_n = 8 \times 10^{-9}\ m^{-1/3}$
Intermediate turbulence	$C_n = 4 \times 10^{-8}\ m^{-1/3}$
Strong turbulence	$C_n = 5 \times 10^{-7}\ m^{-1/3}$

*Reference 4

However, recent experiments[5,6] with finite beams have shown that the variance does not increase indefinitely with range; that the magnitude of the variance increases for ranges up to about 700 m (depending on the strength of turbulence C_n), beyond which no increase is observed. deWolf[7] has suggested new postulation to account for the "saturation" of the variance magnitude. He gives the variance of scintillation magnitude as

$$\sigma^2 = \ln[2 - \exp(-\sigma_T^2)], \qquad (7)$$

where σ_T^2 is given by Equation (6). This formulation, though for infinite wave propagation, has shown reasonable agreement with recent experiments.[6] deWolf has also argued that for long paths through the atmosphere the distribution function associated with the beam cross section perturbation tends from a log-normal to a Rayleigh distribution. The two distributions become markedly dissimilar only for large fluctuations in an intensity signal. Such fluctuations are not reached, however, because of the saturation effect, and recent experimental data[6] have been inconclusive in tests between the two distributions.

IV. EYE DAMAGE MODEL

It is proposed, then, using the above formulations and the specific parameters of a pulsed laser source, to develop an expression for the percentage area of a beam cross section which is above a preselected threshold, keeping range L as the independent variable. Assuming that the energies in a beam cross section are log-normally distributed, the distribution of energy density in an atmospherically perturbed beam takes the form[8]

$$p(E)dE = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(\ln E - \ln E^*)^2}{2\sigma^2}\right] d\ \ln E, \qquad (8)$$

where E^* is defined by $\ln E^*$ being the mean of $\ln E$. (It is emphasized that E^* is not the mean of E.) The value of σ is given by Equation (7). Computation of E^* can be made using the following, giving

$$E^* = \bar{E} \exp(-\sigma^2/2). \qquad (9)$$

The integral of Equation (8) over all E gives unit probability. The parameter of interest at range L is the percentage of the cumulative distribution above the energy density for threshold damage to the eye. This percentage area of the beam cross section above the damage threshold is the probability of damage (PD) represented as

$$PD = 1 - \int_0^{E_T} p(E)dE, \qquad (10)$$

where E_T is the threshold energy density incident at the cornea for retinal damage. Restating Equation (10) gives

$$PD = 1 - \frac{1}{\sqrt{2\pi}\,\sigma} \int_0^{E_T} \exp\left[-\frac{(\ln E - \ln E^*)^2}{2\sigma^2}\right] d\ \ln E. \qquad (11)$$

Thus a set of optical and atmospheric parameters can be chosen and, using Equations (5), (7), and (9), Equation (11) can be integrated for increasing L to give the percentage probability of damage computation as a function of range.

V. SAMPLE COMPUTATIONS

Equation (11) has been evaluated for a pulsed ruby laser rangefinder* having a nominal output energy of 0.1 J at 6943 Å and a solid angle divergence of 0.44 μsr. A value of 10^{-3} J/m^2 has been taken for E_T as established by the U. S. Army Office of the Surgeon General for radiation from a Q-switched ruby laser incident at the cornea.[9,10] (The value of E_T can be increased about an order of magnitude for lasers operating in the normal mode.) Figure 2 shows the parameter probability of damage evaluated as a function of range out to a distance of 10 km. In this figure, a value of 5×10^{-7} m$^{-1/3}$ has been used for C_n. The function is computed for a set of atmospheric attenuation coefficients ranging in magnitude from 0.05 km^{-1} to 1.0 km^{-1}. For this particular laser under high turbulence conditions, the probability of retinal damage from a single corneal illumination can be evaluated as a function of range. Figures 3 and 4 show the probability of damage evaluation for C_n values of 4×10^{-8} m$^{-1/3}$ and 8×10^{-9} m$^{-1/3}$. For smaller values of C_n, the slopes of the probability of damage function become steeper, particularly for high values of σ_A. With low C_n's at short ranges, the breadth of the distribution curve is not great; hence most of the energy densities are distributed near the mean. Particularly for high σ_A's, the ranges at which the lowest and highest energy densities cross below E_T are not separated by many meters. Thus the probability of damge goes quickly from unity to zero. It is also pointed out that some evaluated combinations of atmospheric conditions given are not typical of a real environment. For instance, it is not likely that a high turbulence (e.g., a C_n of 5×10^{-7} m$^{-1/3}$) would persist under fog conditions (σ_A = 1.0 km^{-1}).

The effect of the scintillation considerations on the safety calculations can be observed in Figure 2. Using Equation (5) and a σ_A of 0.05 km^{-1}, the threshold crossover point occurs at about 10 km. For the

Denoted the XM-23 E2 Rangefinder, supplied by Frankford Arsenal, Philadelphia, Pennsylvania.

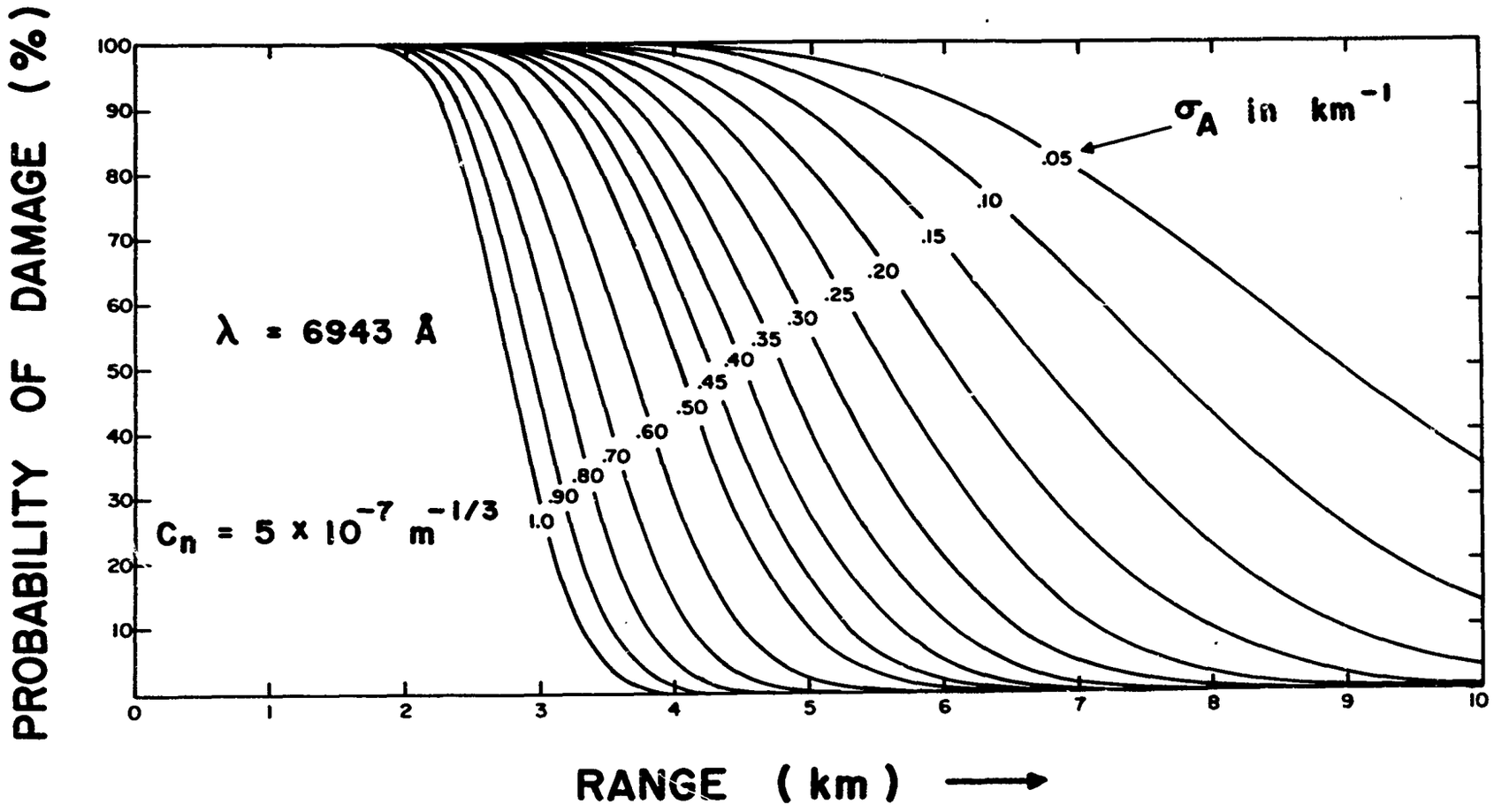

Figure 2. Probability of Damage versus Range for Strong Turbulence (Ω = 0.44 μsr, E_0 = 0.1 J), Log-Normal Distribution)

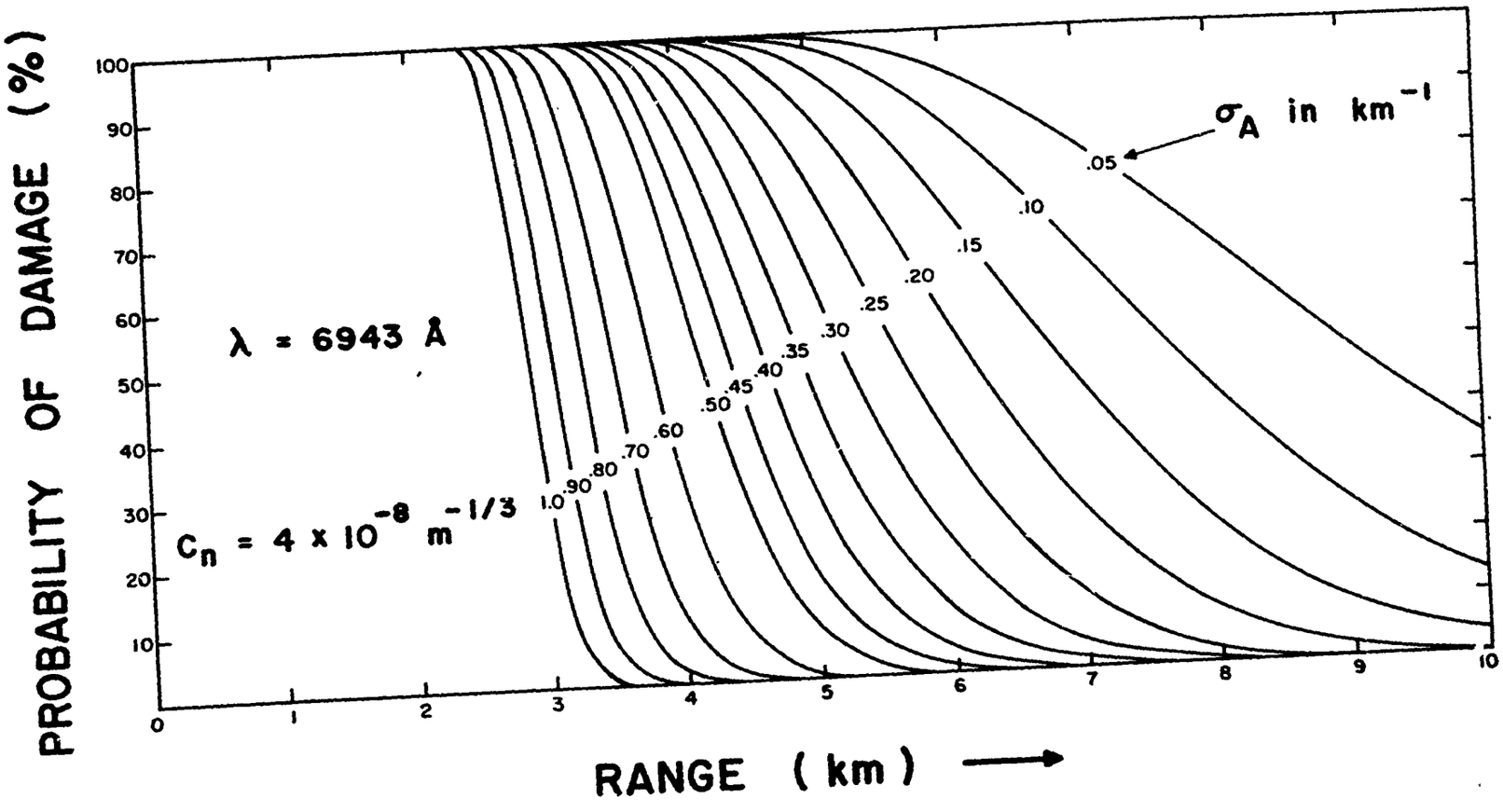

Figure 3. Probability of Damage versus Range for Intermediate Turbulence (Ω = 0.44 μsr, E_0 = 0.1 J), Log-Normal Distribution)

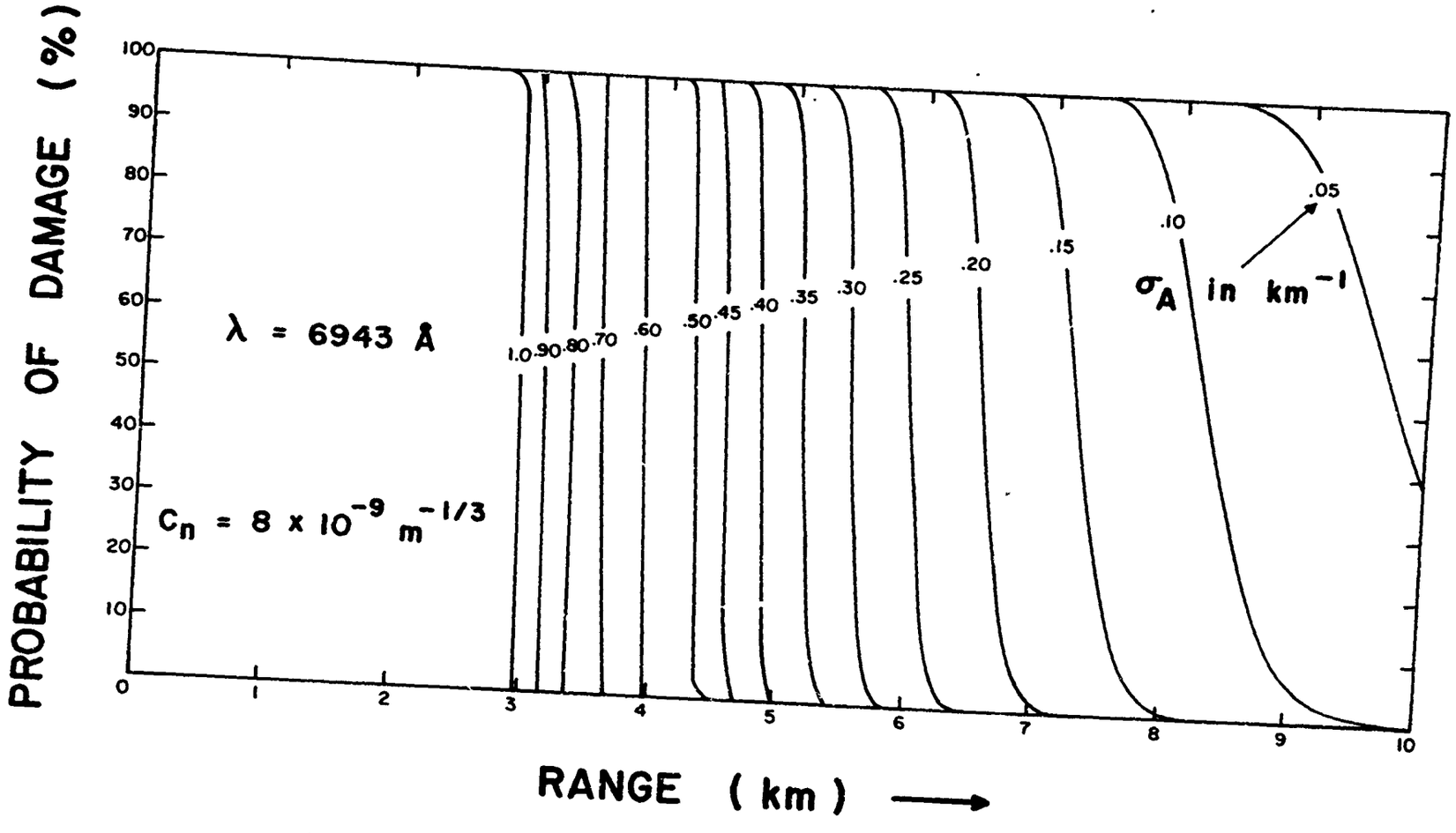

Figure 4. Probability of Damage versus Range for Weak Turbulence (Ω = 0.44 μsr, E_o = 0.1 J), Log-Normal Distribution)

same σ_A under high scintillation conditions, 34 percent of the beam is still above E_T. Thus the decrease in damage probability at shorter ranges is accompanied by an increase in the range at which damage can possibly occur.

VI. RAYLEIGH CALCULATIONS

In Section III, the question of log-normal versus Rayleigh beam statistics was introduced. To examine the effect of Rayleigh statistics on the safety model, the probability of damage function was computed for this second distribution. A Rayleigh distribution[11] can take the form

$$p(E)dE = \frac{1}{m} \exp(-E/m)dE, \qquad (12)$$

being defined for $E \geq 0$ only. The Rayleigh distribution is characterized by a single parameter m which represents both the mean value and the standard deviation. If the Rayleigh distribution is the limiting form for the distribution of energies after saturation has occurred, L and C_n no longer affect the variance of the distribution curve. Thus in Equation (12) m is determined by $\bar{E}$, and the probability of damage takes the form

$$PD = 1 - \int_0^{E_T} \frac{1}{\bar{E}} \exp(-E/\bar{E})dE = \exp(-E_T/\bar{E}). \qquad (13)$$

This function has been evaluated as before, using Equation (5) and the laser parameters given in Section V. Figure 5 shows the evaluation of Equation (13) for a series of σ_A's out to a range of 10 km. Figures 5 and 2 are compared since the Rayleigh distribution is the limit for strong fluctuations in the index field and long paths. The Rayleigh calculations cross over the log-normal values at about a 10-km range, showing slightly lower damage probabilities for shorter ranges. In the limit of long ranges and high turbulence, the Rayleigh and log-normal analyses give similar results.

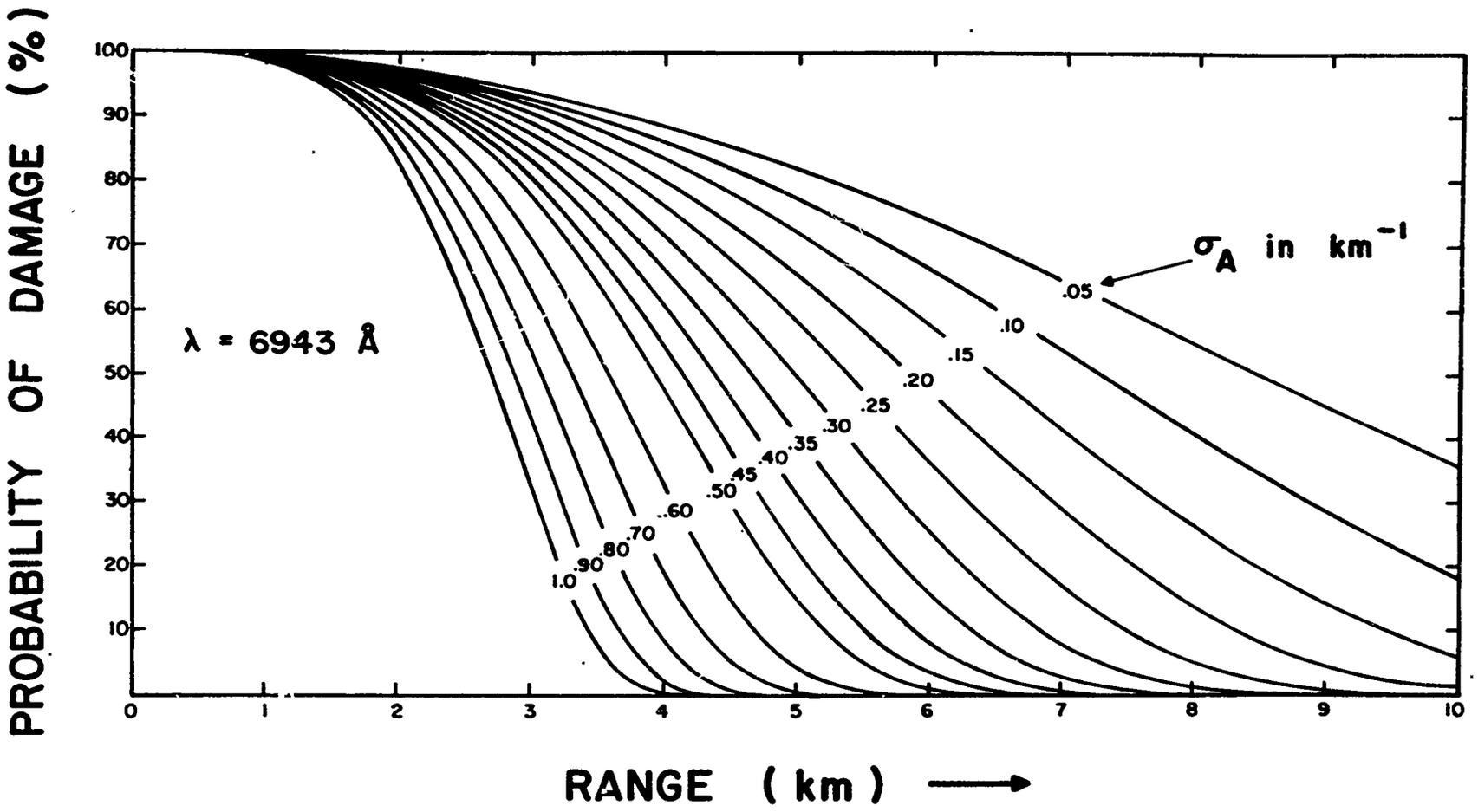

Figure 5. Probability of Damage versus Range (Ω = 0.44 μsr, E_0 = 0.1 J), Rayleigh Distribution

VII. SAFETY NOMOGRAPH

To facilitate the evaluation of Equation (11) for various laser parameters and atmospheric conditions, a series of nomographs was developed. A nomograph was computed for each of four representative σ_A's at three levels of turbulence. Figure 6 shows the safety nomograph computed for strong turbulence ($C_{n_o} = 5 \times 10^{-7}\ m^{-1/3}$), a σ_A of 0.05 km^{-1}, and an optical wavelength of 6943 Å. The ordinate can be understood to represent a normalized energy density plotted against range out to 10 km. Having chosen a value of σ_A in Equation (5), the ratio of $\bar{E}\Omega/0.7\ E_o$ becomes a function only of L. This ratio, the average normalized energy $\bar{E}_n$, is shown as a solid line in the figure. This line is given simply by the inverse square law modified by the Bouguer exponential. To find the crossover range of $\bar{E}_n$, E_T is inserted in the above ratio for $\bar{E}$ along with the appropriate values of Ω and E_o. The resulting number is then found on the ordinate, and a line is extended horizontally. The intersection of this line with $\bar{E}_n$ indicates the safe range for the laser neglecting scintillation. To account for the effects of scintillation, Equation (11) has been evaluated to six cumulative probability levels around $\bar{E}_n$. For example, at a given range, the lowest dashed line indicates that 98 percent of the beam is above that level of energy density (relative to the $\bar{E}_n$ directly above). To find the probability of damage for the rangefinder evaluated earlier in Figure 2 for a σ_A of 0.05 km^{-1}, the ratio of $E_T\Omega/0.7E_o$ is computed using 0.1 J for E_o, 0.44 μsr for Ω, and the value of 10^{-3} J/m^2 for E_T. This gives a value of approximately 6.4×10^{-9} for the ordinate. A horizontal line extended from this reference intercepts the probability flow lines at about the ranges indicated by the 0.05 σ_A line of Figure 2. The ratio can also be considered a safety parameter. For a given range on the nomograph, the minimum tolerable ratio of Ω/E_o for safe operation can be easily derived. Twelve eye safety nomographs for various σ_A's and C_n's are presented in the Appendix.

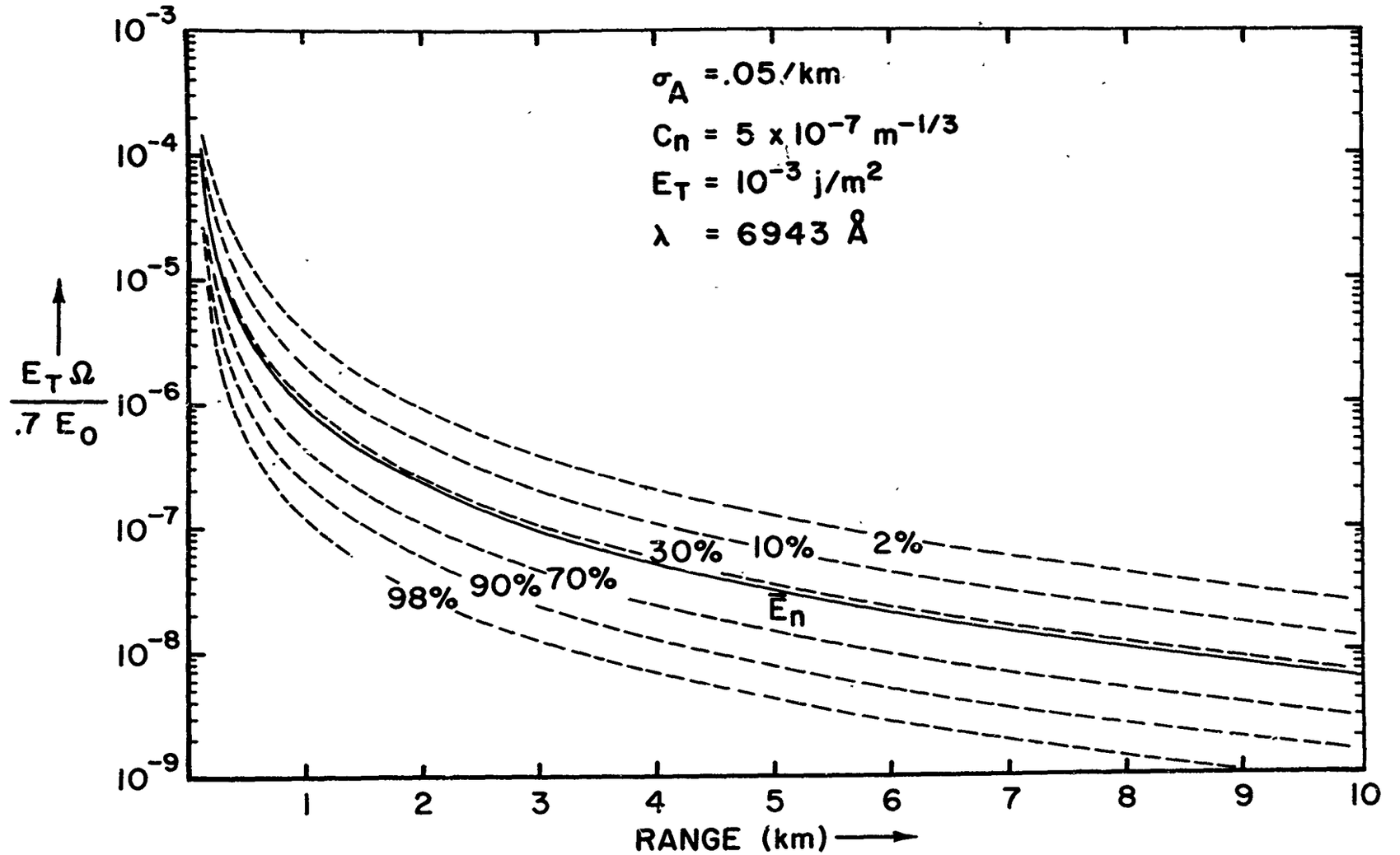

Figure 6. Eye Safety Nomograph ($C_n = 5 \times 10^{-7} m^{-1/3}$, $\sigma_A = 0.05/km$)

VIII. DISCUSSION

One of the problems associated with analysis of current laser systems is that the beam cross sections are often characterized by high contrast intensity profiles resulting from Q-switching elements or transmitter optics. The formulas used in the analysis assume a homogeneous wave front entering the turbulence and give the variance about a stationary average intensity. It is suggested for lasers with a profile that the safety analysis be accomplished by dividing the beam cross section pattern into a series of regions of approximately homogeneous energy density. The probability of damage analysis would then be applied to a set of density regions, each characterized by a divergence into which a fraction of the laser output would radiate (thus modifying the number 0.7 appearing in the safety ratio, according to the fraction of E_o radiated to a given region).

It should be emphasized that the scintillation equations used in the analysis [(Equations (6) and (7)] have been tested only for ranges out to about 1.8 km.[5,6] There are indications that the variance does not remain constant with range after saturation has occurred [Equation (7)], but may, in fact, decrease. If this effect is real, it may indicate the inapplicability of infinite beam theory to finite beams at long ranges. It is thought, however, for the purpose of the laser safety evaluation, that the use of a larger variance than required will result in probability of damage parameters more stringent than necessary.

Finally, the above analysis has been accomplished using a wavelength term of 6943 Å. A similar set of nomographs has been computed for a wavelength of 1.06 μm, resulting in a nearly identical series of curves to those computed for the ruby wavelength. Initial tests of the wavenumber dependence indicate agreement with the theoretical scaling given in Equation (6) (unpublished results). It is expected that an important parameter for the evaluation of beam propagation effects in the near IR is the magnitude of the atmospheric attenuation due to water vapor absorption. For these wavelengths, the atmospheric

attenuation coefficient σ_A cannot be computed directly from the "visibility" V. However, it is believed that the nomographs can be used for lasers in the near IR provided the attenuation and damage threshold (the value of E_T can be increased by a factor of five or six for a laser at 1.06 μm wavelength[12]) parameters are properly chosen.

ACKNOWLEDGMENT

The author gratefully acknowledges the assistance of N. J. Wright in the computation of the probability graphs and J. Lanahan for the evaluation of the safety nomograph. In addition, thanks are expressed to A. Celmins for his helpful criticism.

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APPENDIX

TWELVE EYE SAFETY NOMOGRAPHS

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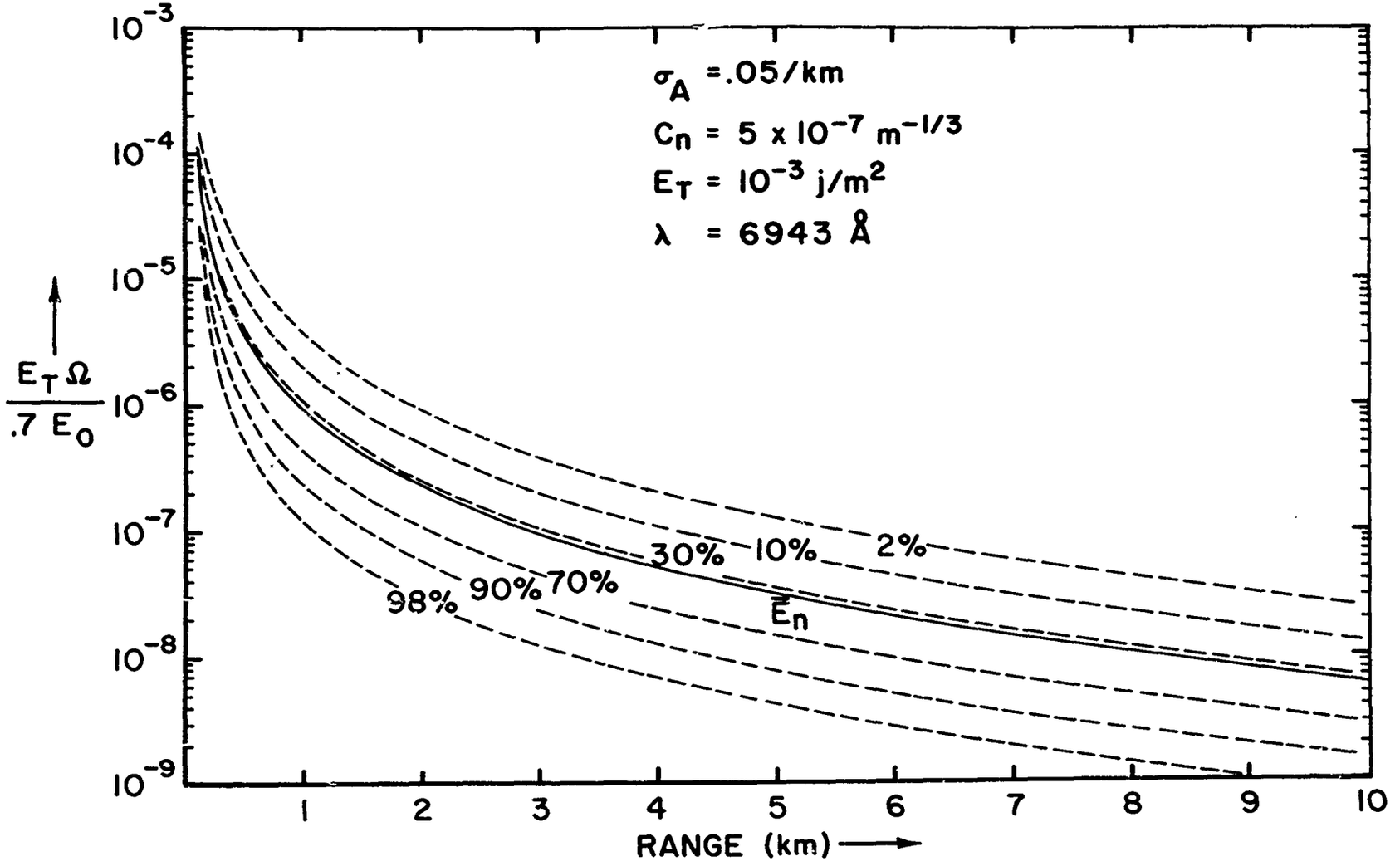
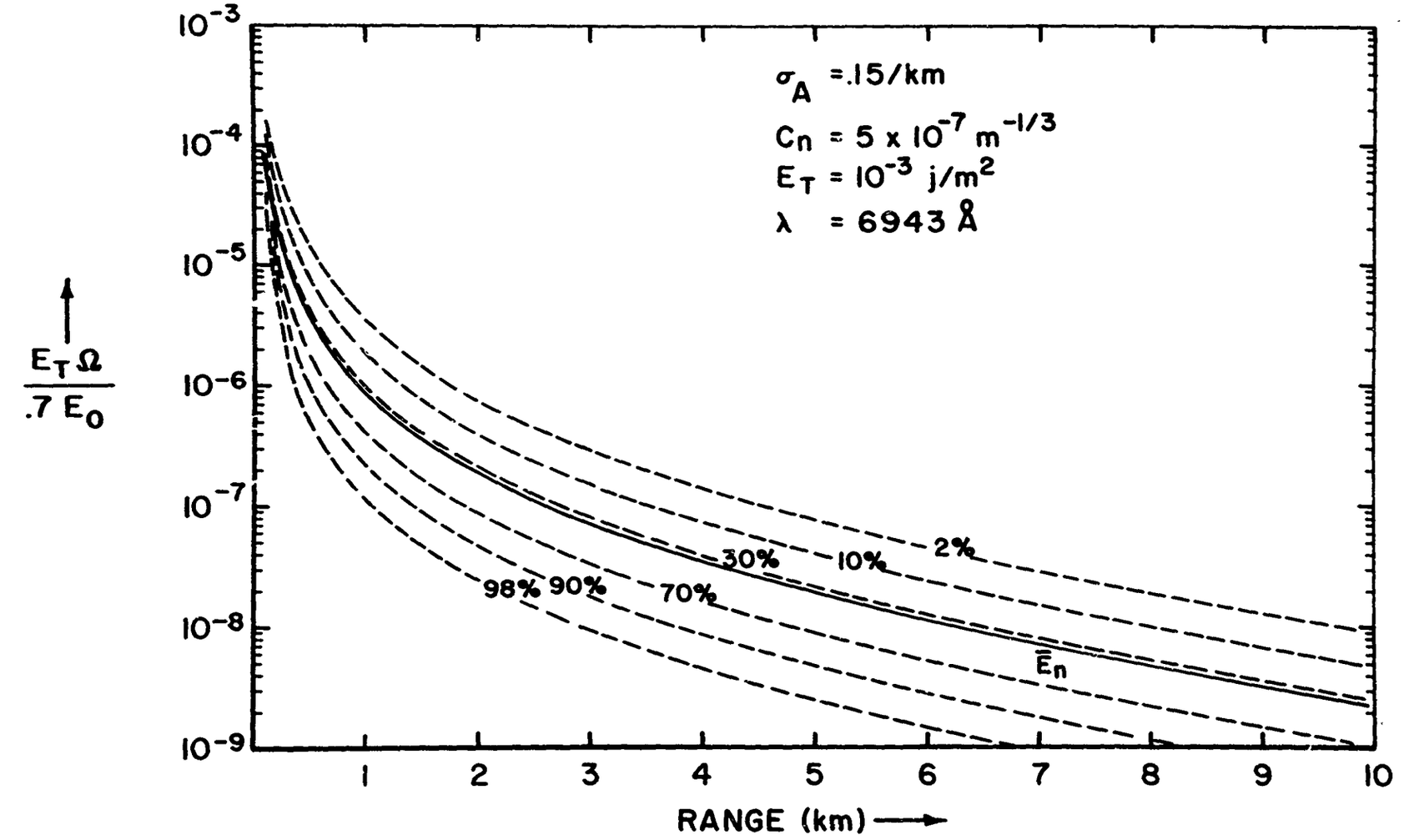

σ_A =.05/km
C_n = 5 x 10^{-7} $m^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$\frac{E_T \Omega}{.7 E_0}$
2%
10%
30%
En
70%
90%
98%
1
2
3
4
5
6
7
8
9
10
RANGE (km)

Figure A-1


σ_A = .15/km
C_n = 5 x 10^{-7} $m^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
1
2
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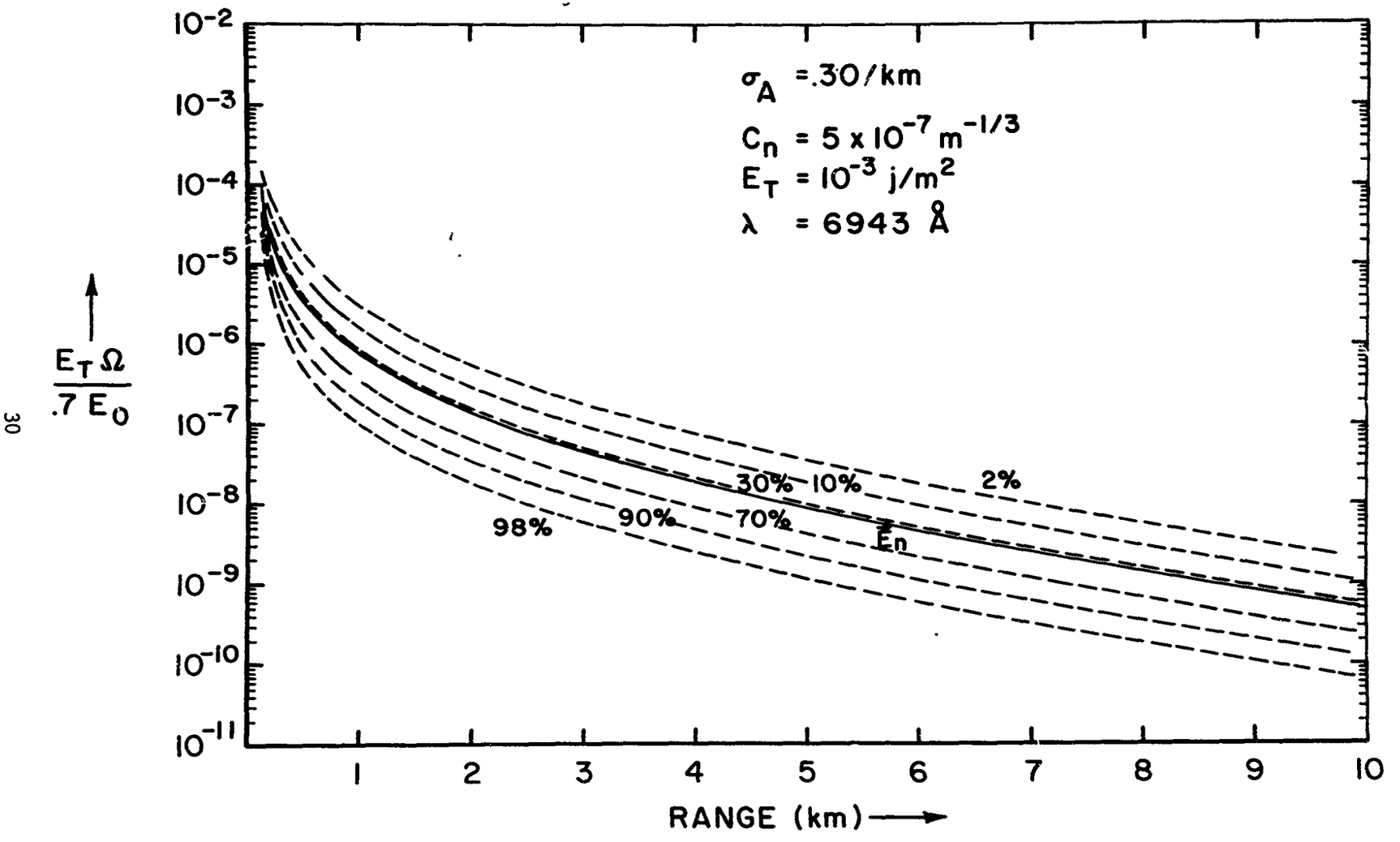
5
6
7
8
9
10
RANGE (km) ⟶
$\frac{E_T \Omega}{.7 E_0}$

Figure A-2


σ_A =.30/km
$C_n = 5 \times 10^{-7}\ m^{-1/3}$
$E_T = 10^{-3}\ j/m^2$
λ = 6943 Å
$\frac{E_T \Omega}{.7 E_0}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
2%
10%
30%
70%
90%
98%
E_n
1
2
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5
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7
8
9
10
RANGE (km)

Figure A-3

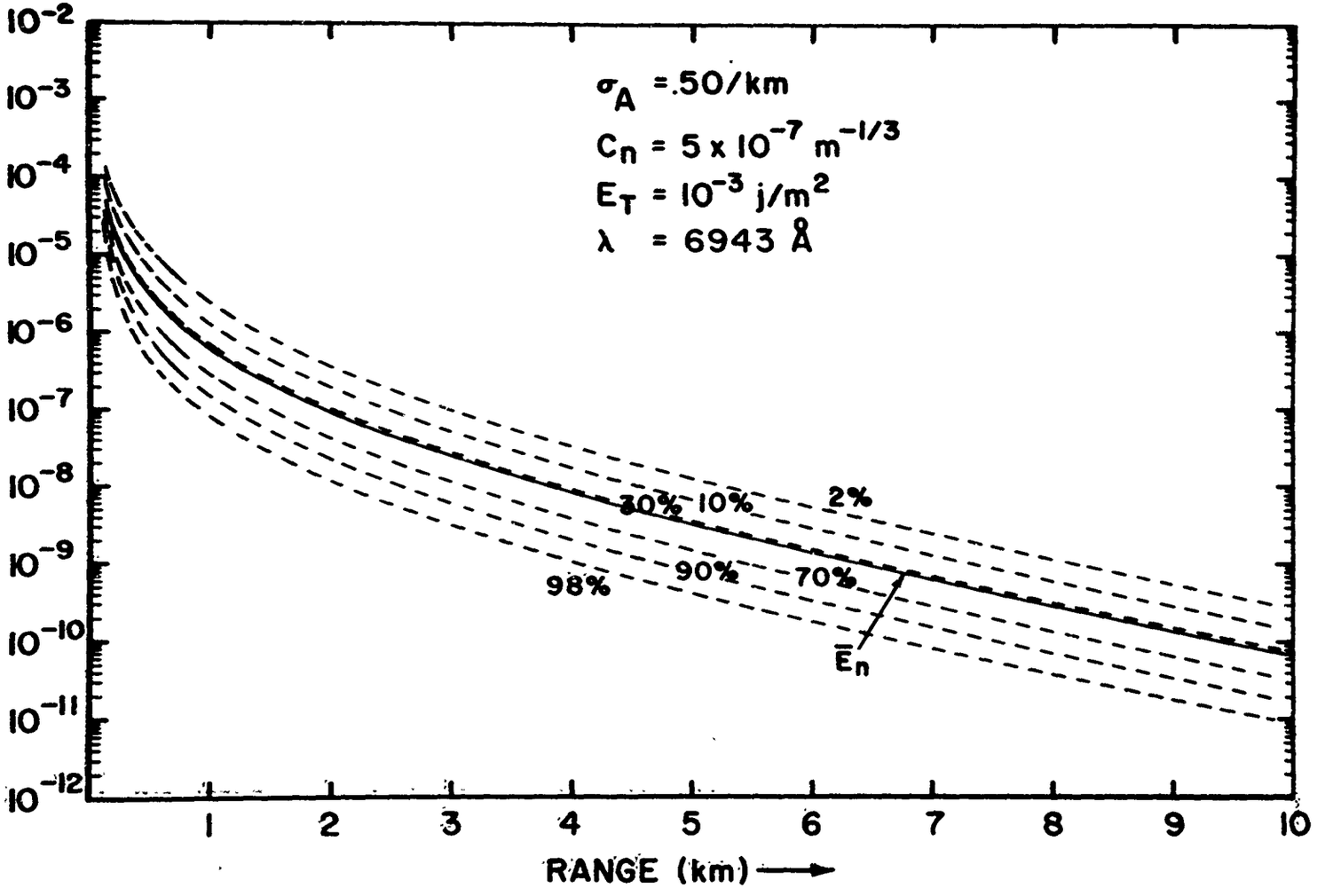
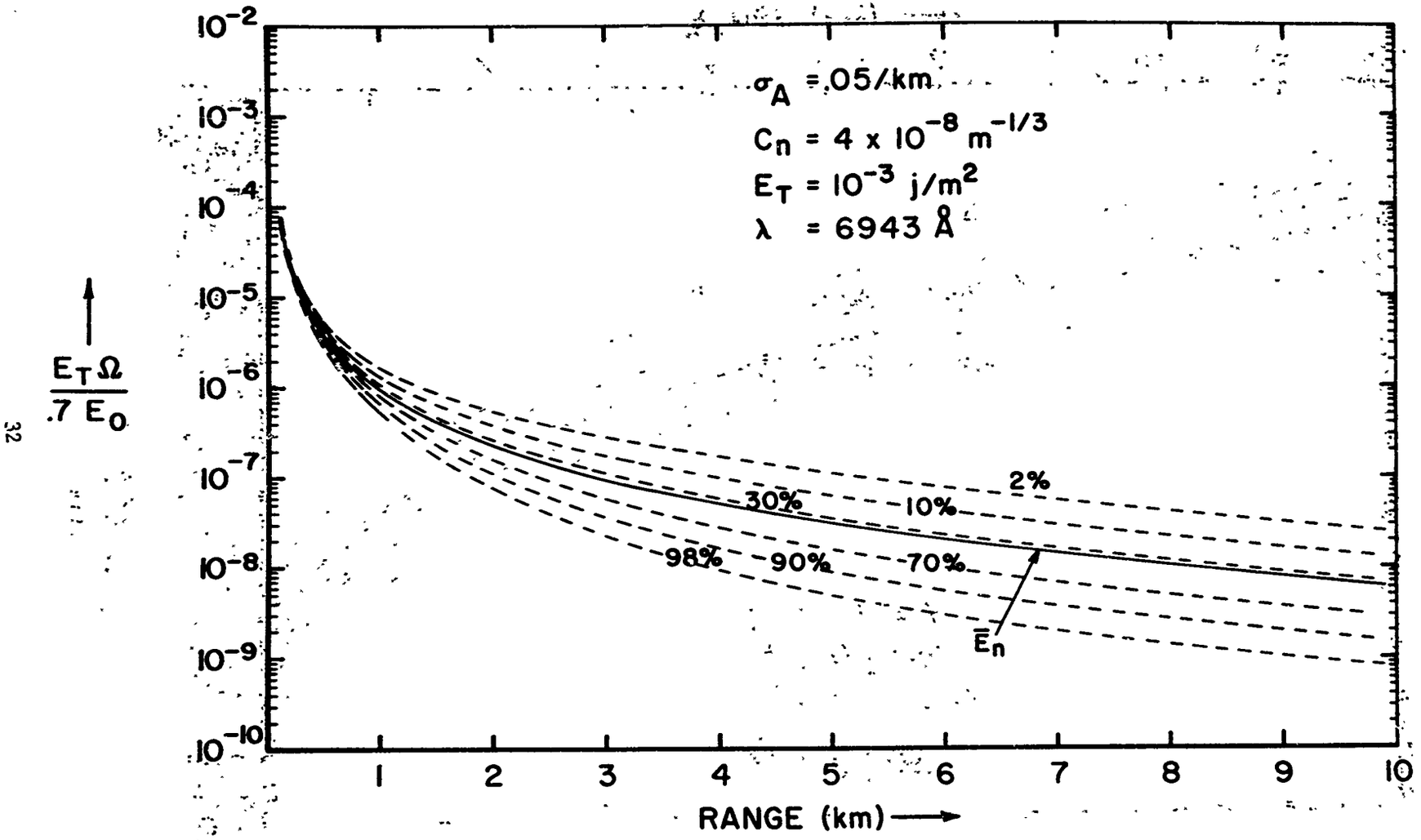

σ_A =.50/km
$C_n = 5 \times 10^{-7}\ m^{-1/3}$
$E_T = 10^{-3}\ j/m^2$
λ = 6943 Å
30%
10%
2%
98%
90%
70%
$\bar{E}_n$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
1
2
3
4
5
6
7
8
9
10
RANGE (km) ⟶
$\frac{E_T \Omega}{.7\ E_0}$

Figure A-4


σ_A = .05/km
C_n = 4 x 10^{-8} $m^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1
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3
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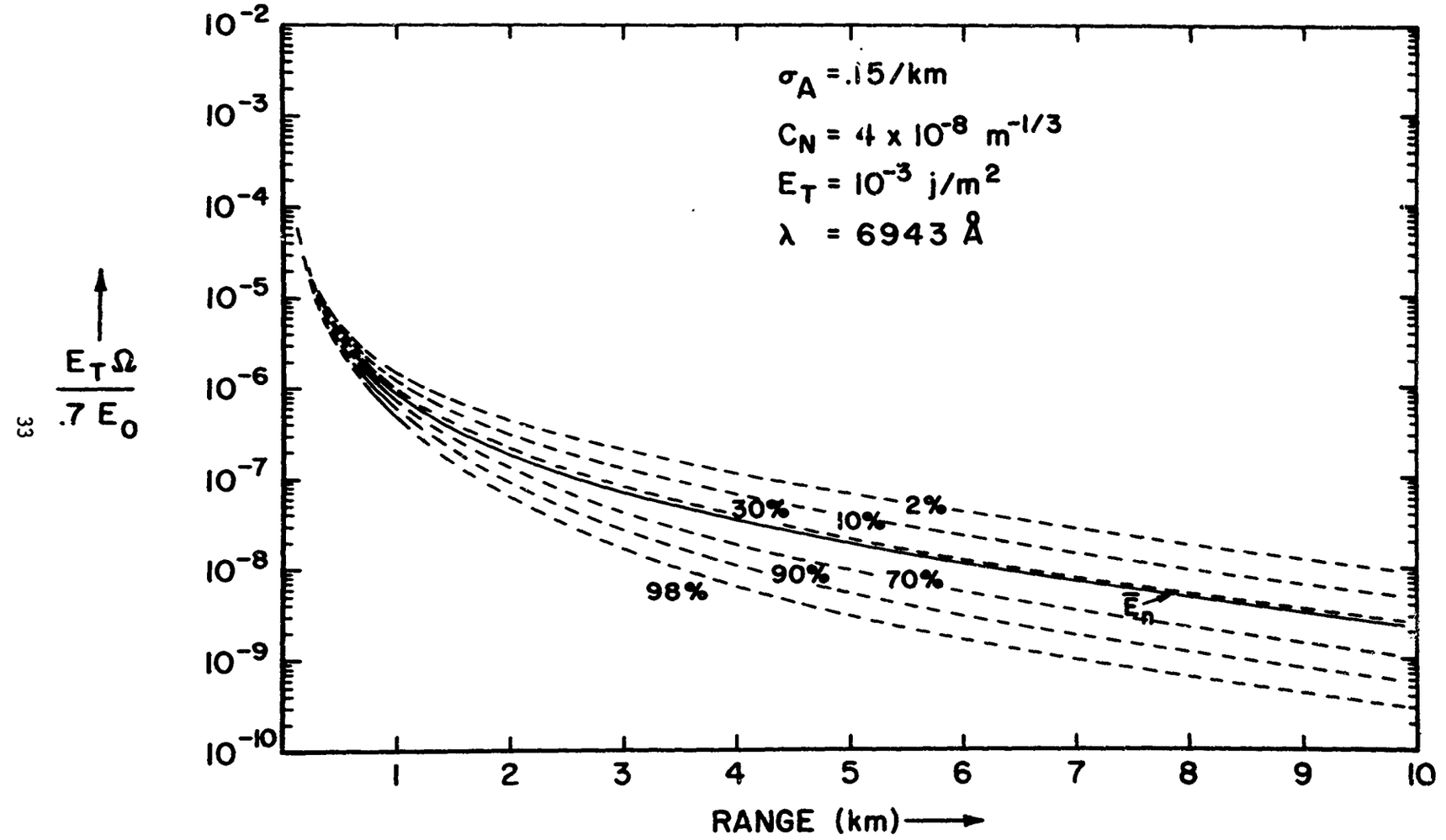
6
7
8
9
10
RANGE (km) ⟶
$\frac{E_T \Omega}{.7 E_0}$

Figure A-5


σ_A = .15/km
C_N = 4 x 10^{-8} $m^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
1
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4
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6
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8
9
10
RANGE (km)
$\frac{E_T \Omega}{.7 E_0}$

Figure A-6

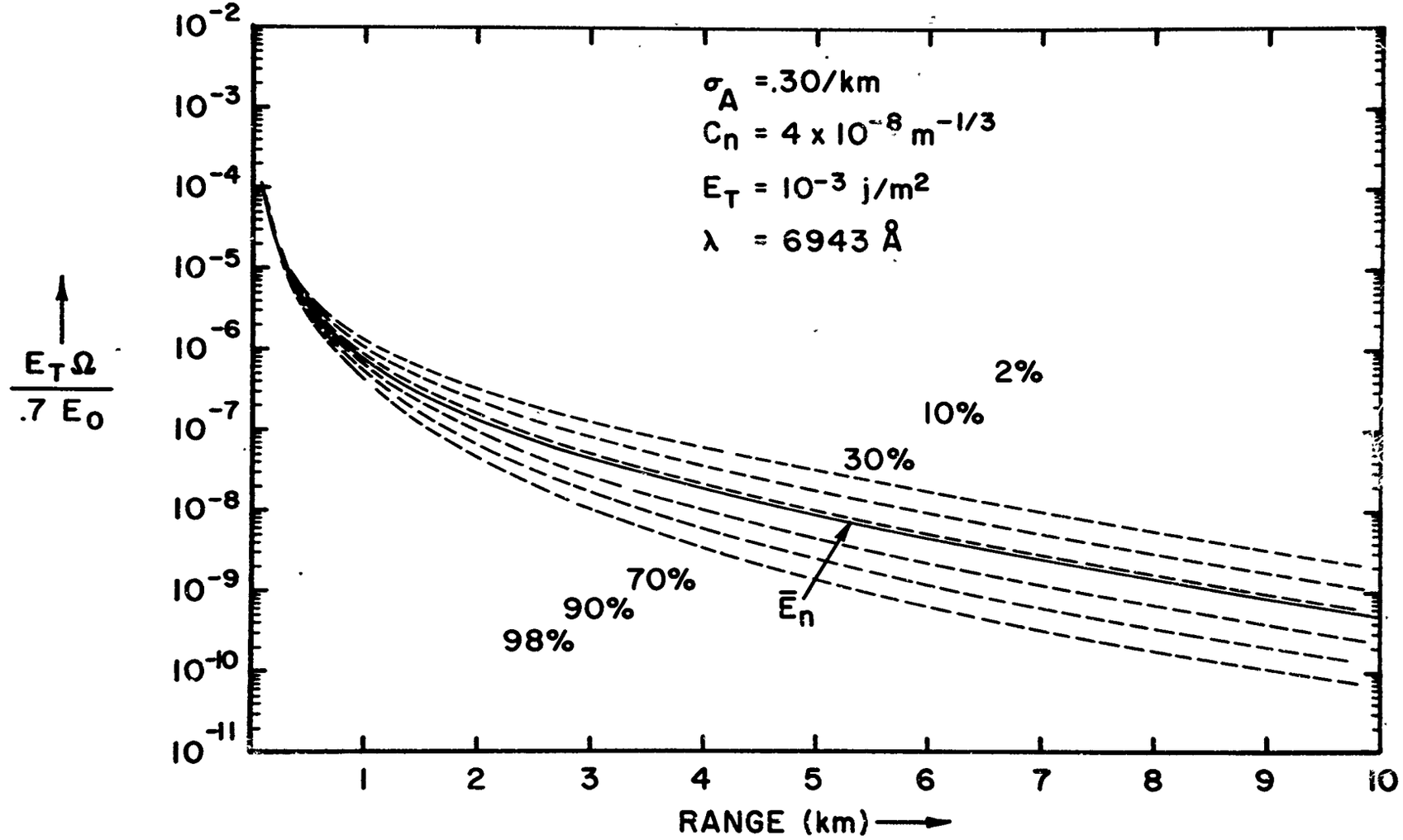
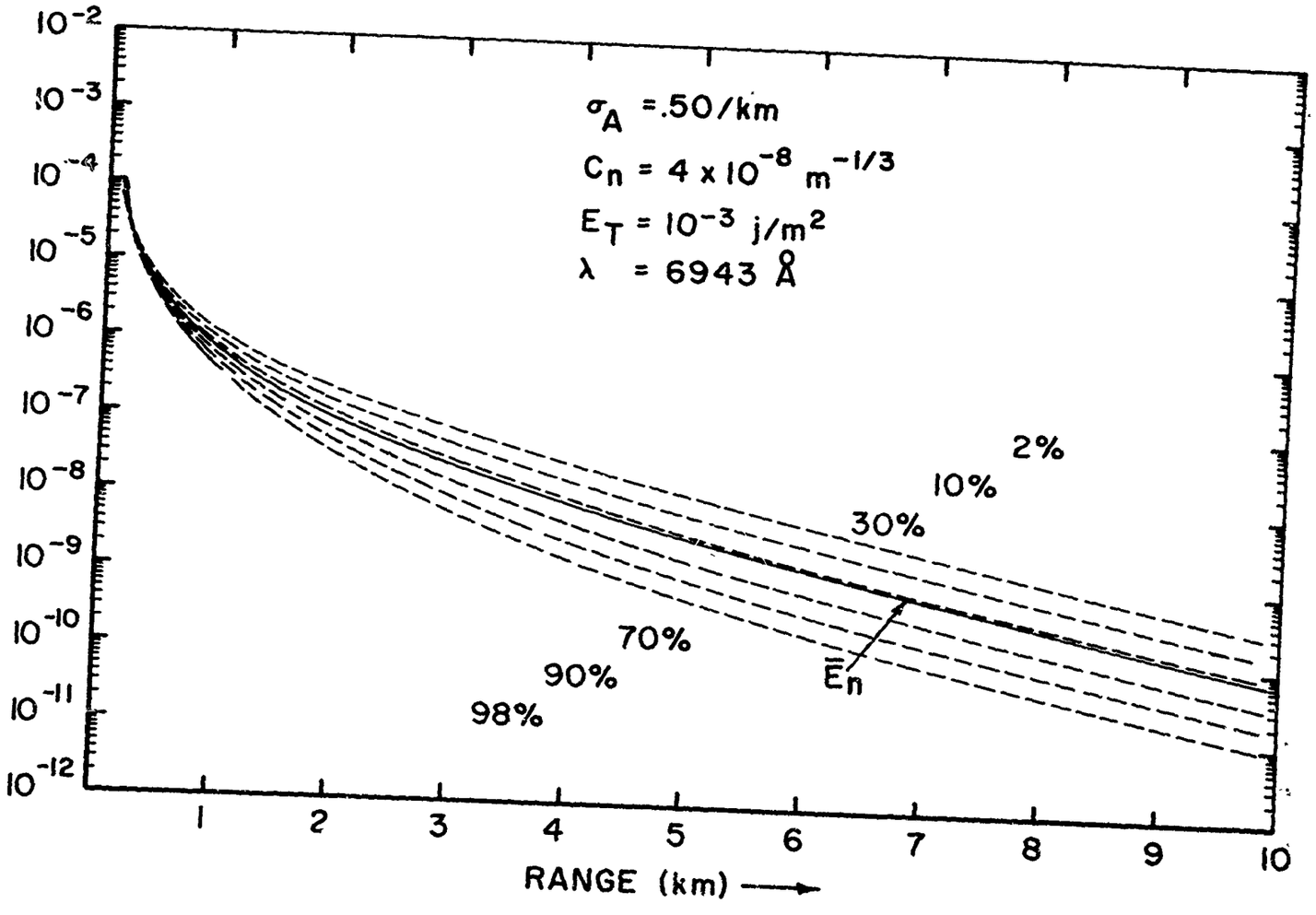

σ_A =.30/km
C_n = 4 x 10^{-8} m$^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
$\frac{E_T \Omega}{.7\ E_0}$
RANGE (km)

Figure A-7


σ_A =.50/km
$C_n = 4 \times 10^{-8}\ m^{-1/3}$
$E_T = 10^{-3}$ j/m^2
λ = 6943 Å
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
$\frac{E_T \Omega}{.7\ E_0}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
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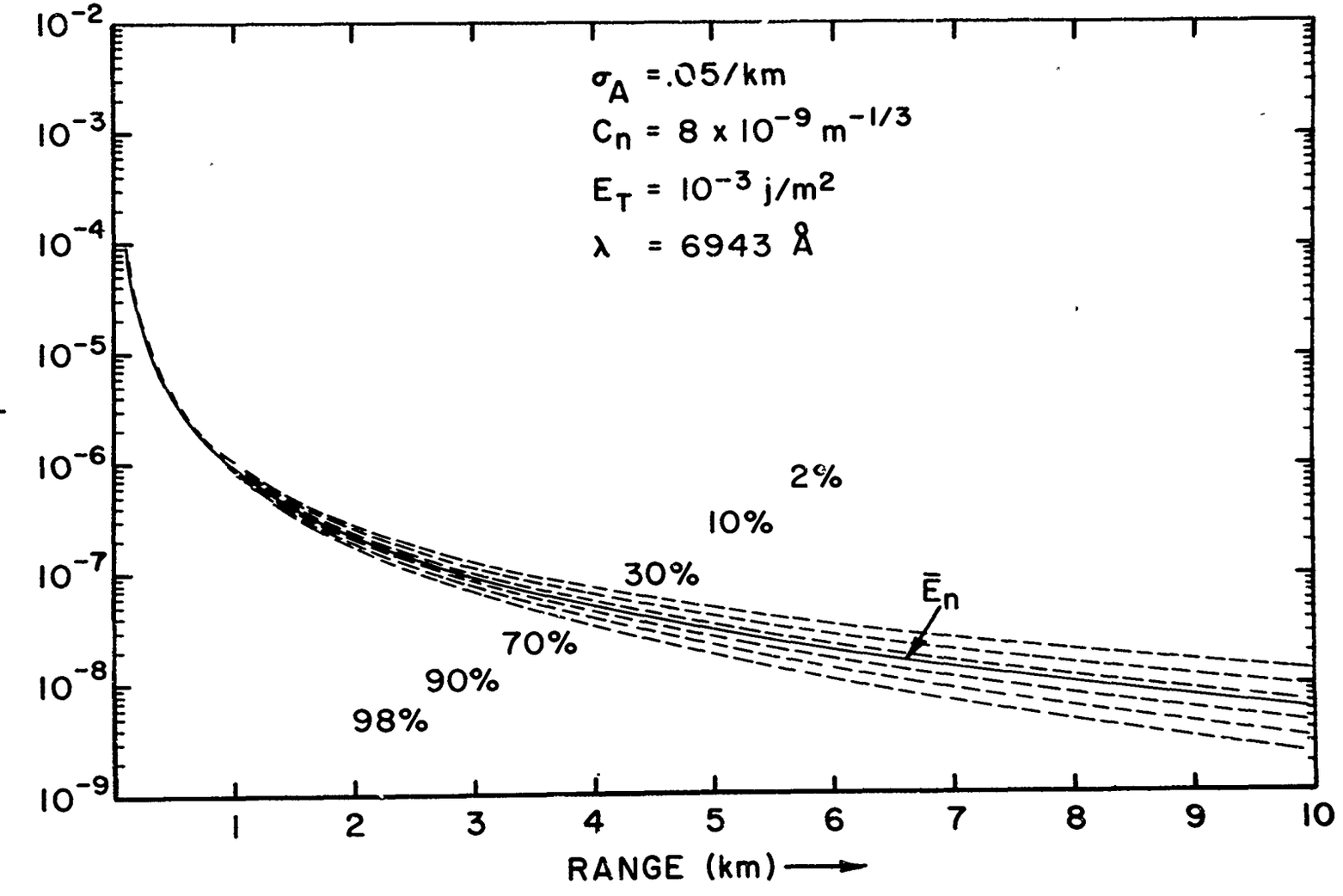
RANGE (km) ⟶

Figure A-8


σ_A = .05/km
C_n = 8 x 10^{-9} $m^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
$\frac{E_T \Omega}{.7 E_0}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
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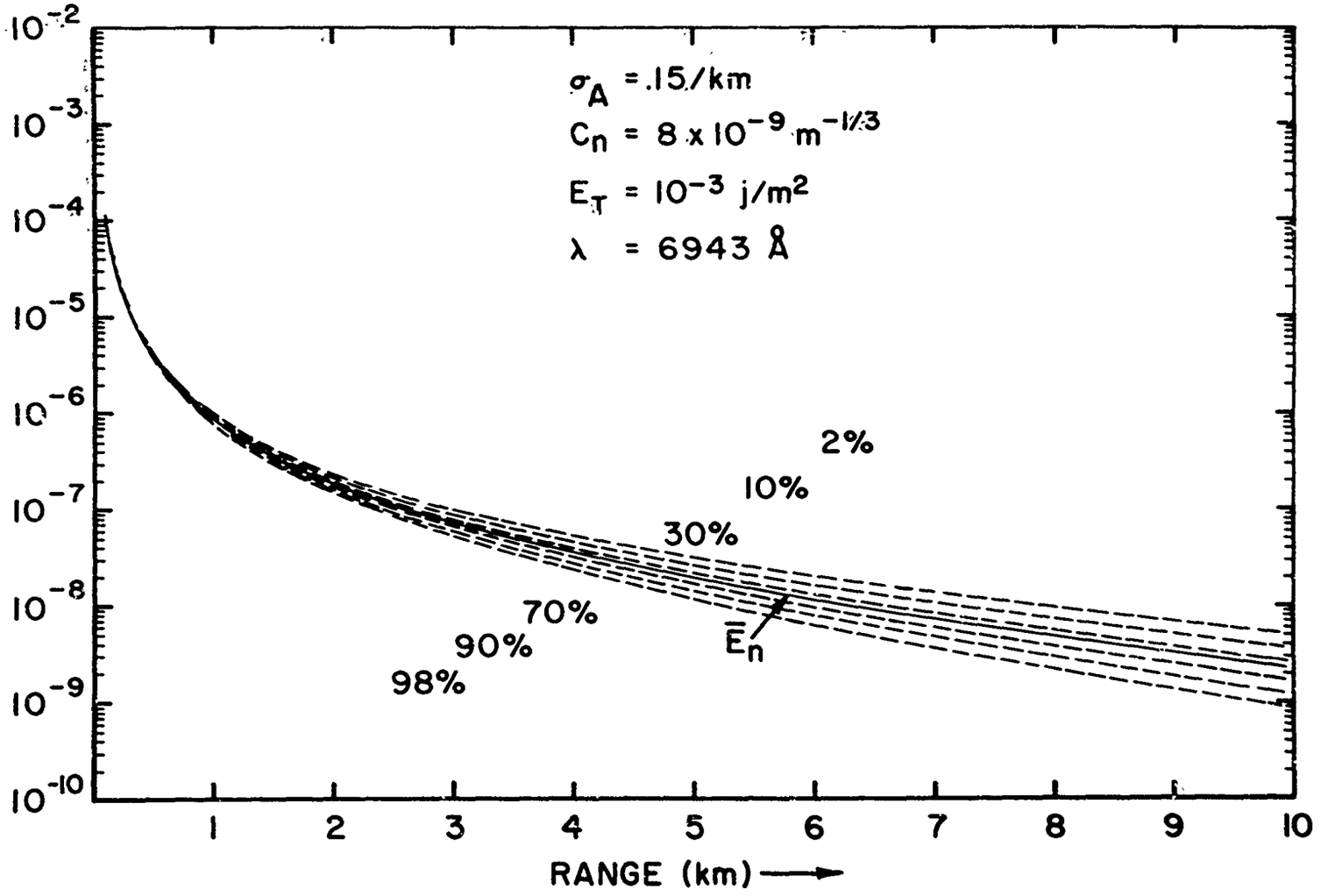
RANGE (km) ⟶

Figure A-9


σ_A = .15/km
C_n = 8 x 10^{-9} m$^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
$\frac{E_T \Omega}{.7\ E_0}$
10^{-2}
10^{-3}
10^{-4}
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10^{-7}
10^{-8}
10^{-9}
10^{-10}
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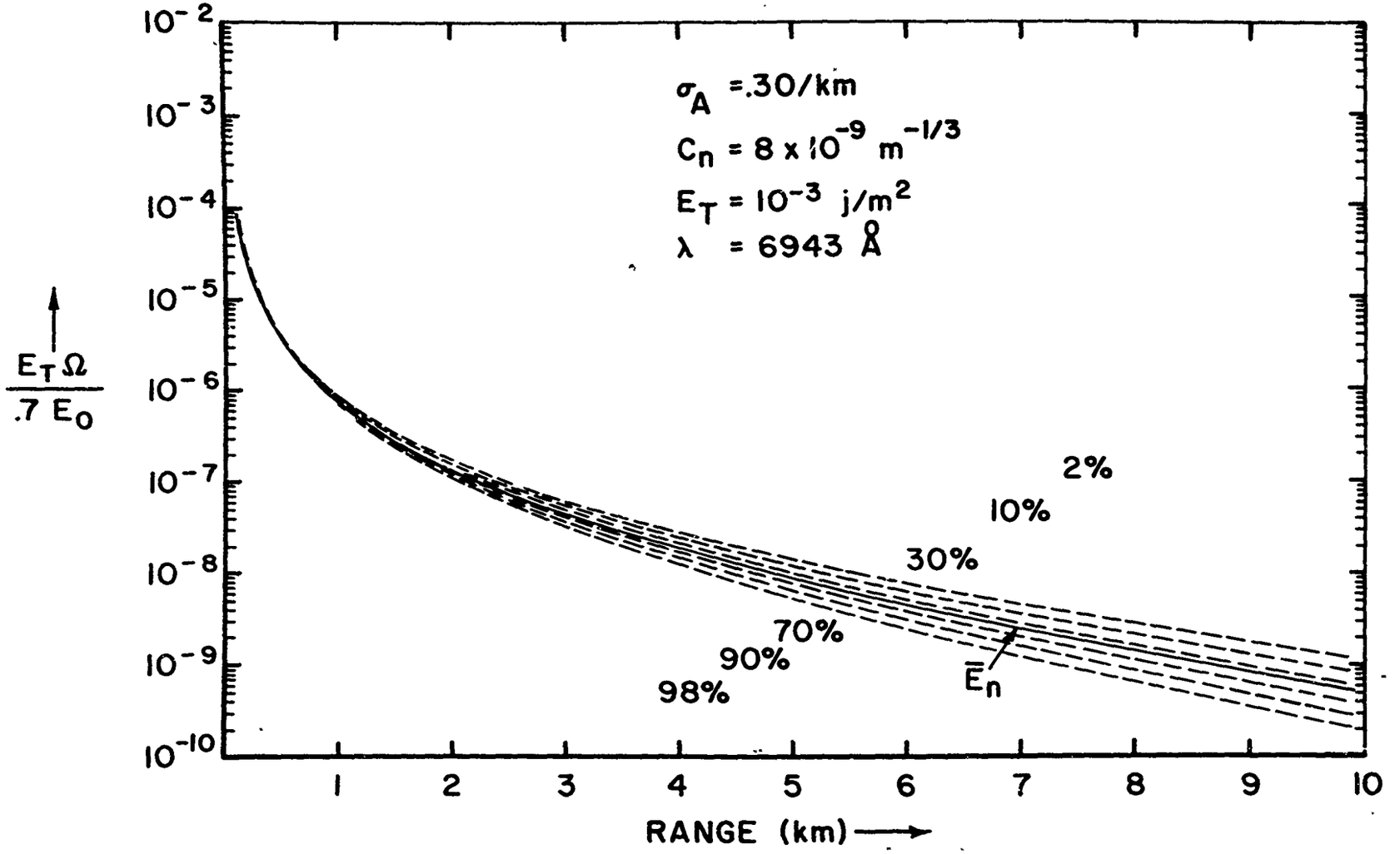
RANGE (km)

Figure A-10


σ_A =.30/km
$C_n = 8 \times 10^{-9}\ m^{-1/3}$
$E_T = 10^{-3}$ j/m^2
λ = 6943 Å
$\frac{E_T \Omega}{.7\ E_0}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
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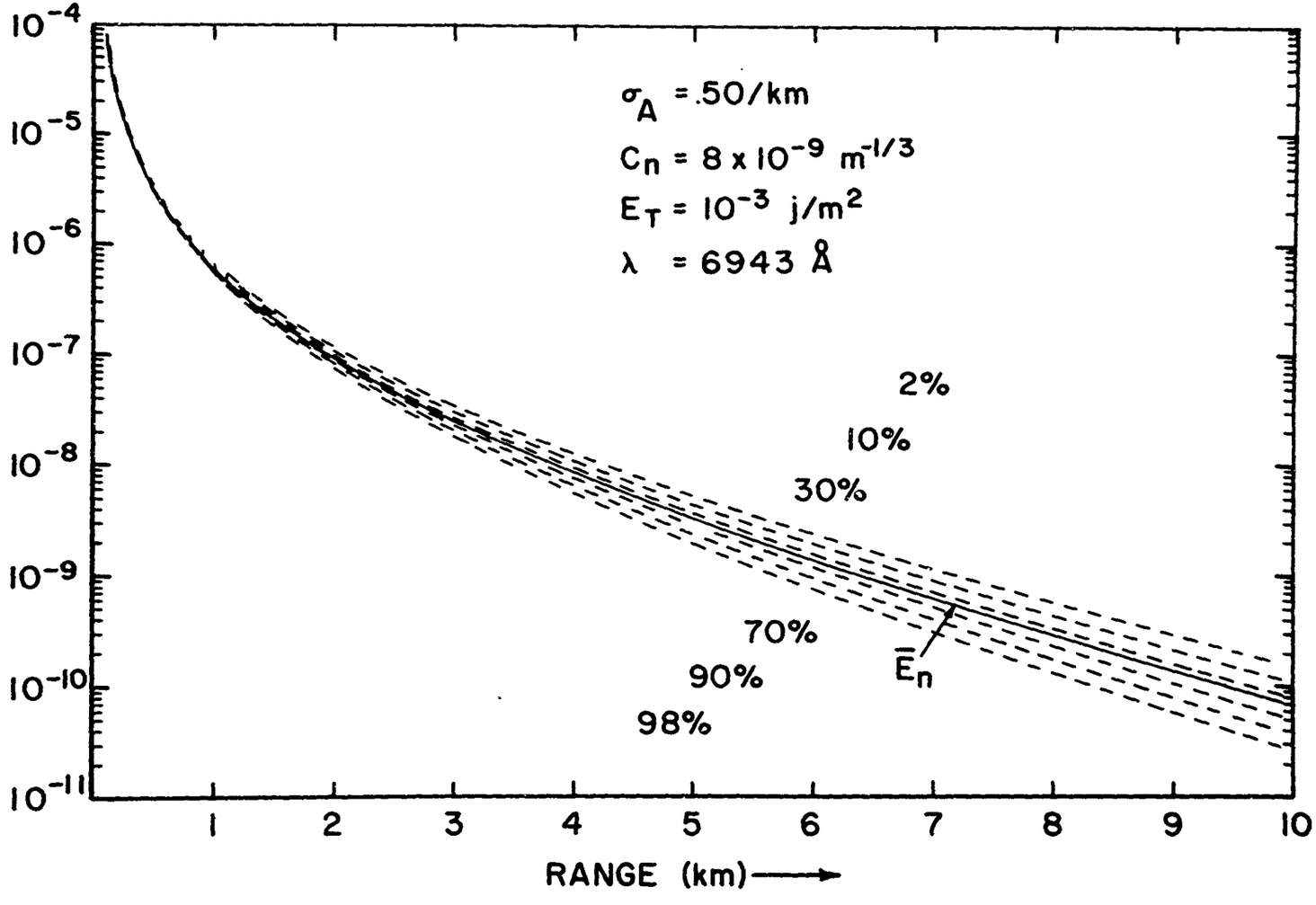
RANGE (km) ⟶

Figure A-11


σ_A = .50/km
C_n = 8 x 10^{-9} m$^{-1/3}$
E_T = 10^{-3} j/m^2
λ = 6943 Å
2%
10%
30%
70%
90%
98%
$\bar{E}_n$
$\frac{E_T \Omega}{.7 E_0}$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
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RANGE (km)

Figure A-12

Unclassified

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13. ABSTRACT

A mathematical model is developed which predicts the probability of ocular damage occurring to personnel illuminated by a pulsed laser beam as a function of the appropriate optical and atmospheric parameters. The evaluation includes terms for the laser output energy and divergence, and atmospheric parameters of attenuation and scintillation. Sample computations are shown, and a safety nomograph is developed to facilitate the eye hazard analysis.

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Laser safety Laser propagation Atmospheric turbulence Atmospheric attenuation						